

Session #4: Technical Issues *Cladding*

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**2015 Division of Spent Fuel Management (DSFM)
Regulatory Conference (REG CON 2015)**
Washington, DC
November 18-19, 2015

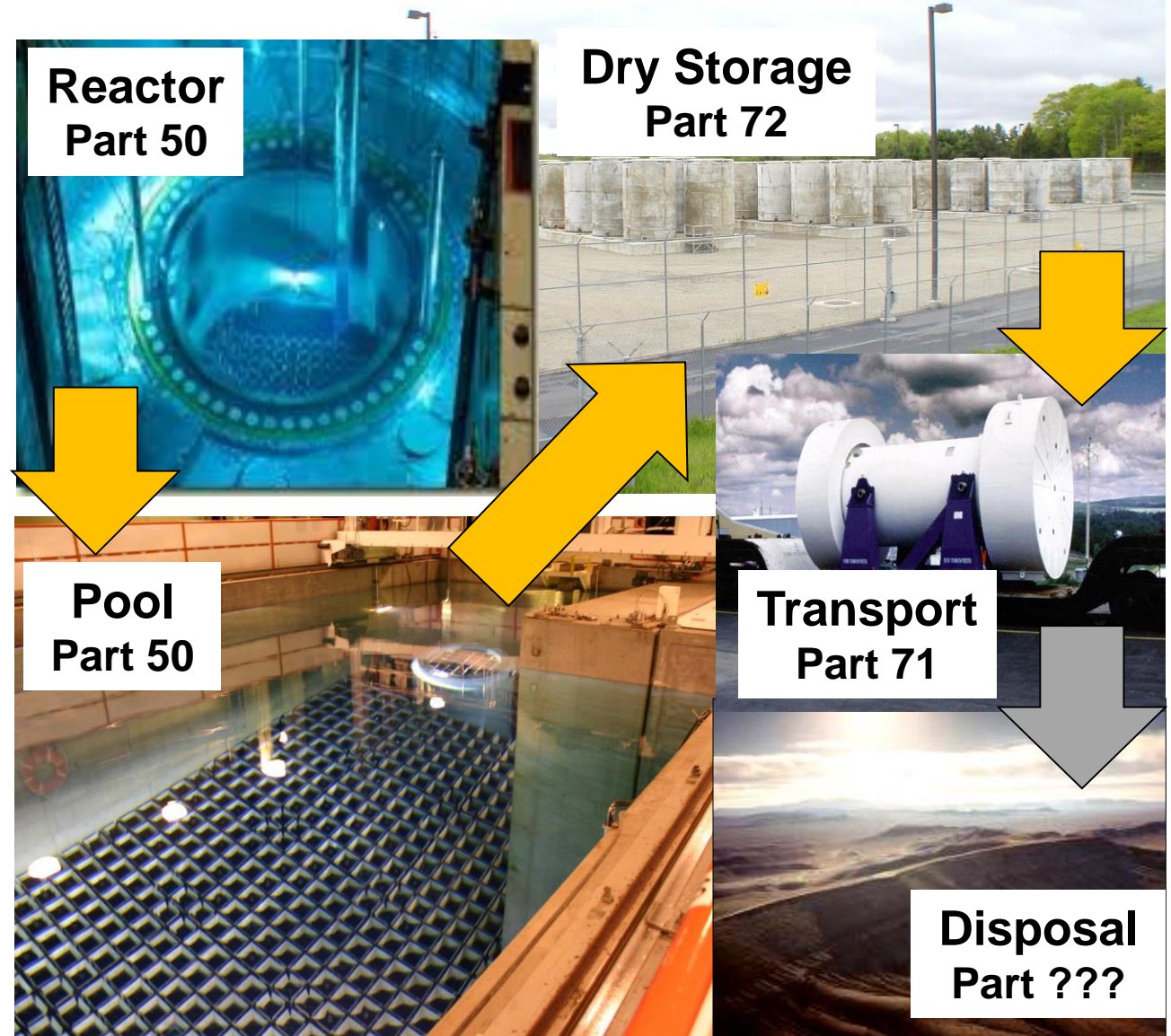


Topics

- Cladding Performance Challenges
- R&D Drivers
- White Paper Scope
- Conclusion

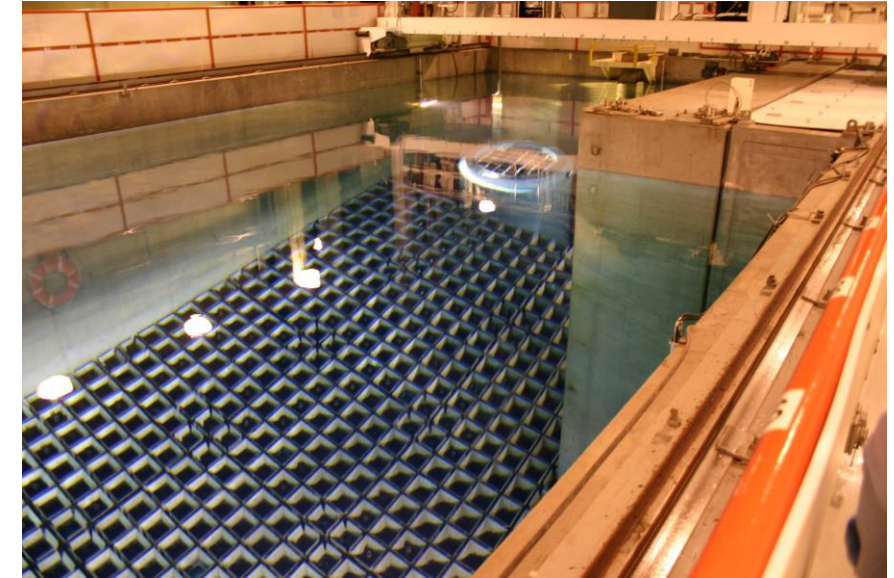
Nuclear Fuel Design/Performance

- Nuclear fuel is designed for robust in-reactor performance
 - In-reactor conditions are more challenging than storage conditions
 - Fuel temperature
 - Waterside corrosion
 - Flow conditions
 - Neutron flux
- Expected cladding performance after reactor duty



Storage

- Fuel rods' internal pressures are no longer “counter-balanced” by reactor system pressure
 - Already true during initial wet storage period
- Transfer from wet to dry storage results in:

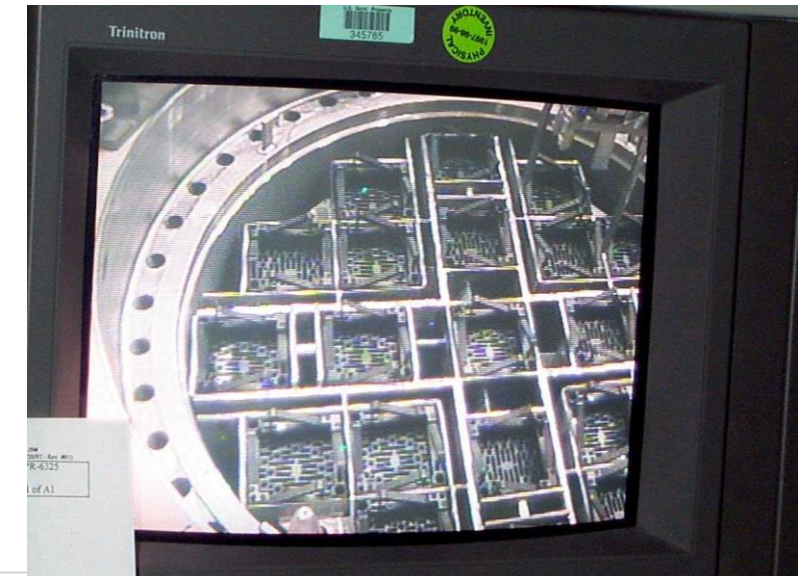


Increases in cladding **hoop stress** by a factor <2

Increases in cladding **temperature**

Driving force

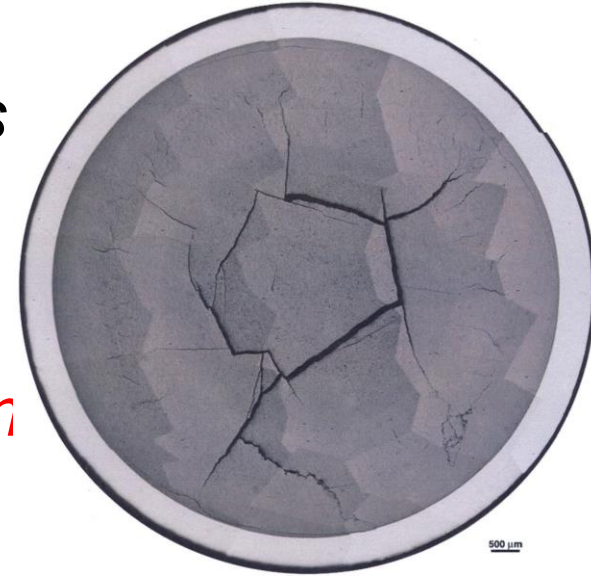
Rate Control



Fuel and Fuel Cladding Degradation Mechanisms

- *Air Oxidation*
- *Stress Corrosion Cracking*
- *Thermal Creep and Creep Rupture*
- *Hydride Re-orientation and Migration and Impact on Cladding Mechanical Properties*
- *Delayed Hydrogen Cracking (DHC)*

- *Cladding hoop stress depends*
 - *Rod internal pressure*
 - *Gas content*
 - *He pre-pressurization*
 - *(He from decay)*
 - *He from ^{10}B (W IFBA rods)*
 - *Fission gas release*
 - *Volume available for gaseous species*
 - *Temperature*
 - *Fuel-cladding bonding (high burnup)*



Dry Storage of High Burnup Fuel – *EPRI Conclusions*

- Potential cladding degradation mechanisms
 - Thermal creep
 - *Self-limiting mechanism*
 - Delayed Hydride Cracking (DHC)
 - *Large incipient defects required*
 - Hydride re-orientation
 - *Expected to be limited*
 - *Not a concern for BWR “Barrier Cladding”*
- Note: A small number of fuel rod failures is not ruled out during pre-storage and storage operations (In U.S.: >10 000 000 rods in dry storage), *but gross fuel ruptures are not predicted under normal and off-normal conditions*
 - *Stored energy (i.e., mechanical energy or “ $p \cdot V$ ” term) in the rod is small*
 - *No dynamic propagation of axial cracks*



Kim Gruss et al., TOPFUEL Meeting, Wurzburg , Germany (2003)

*“In general, these data and analyses support the conclusions that: (1) deformation caused by **creep** will proceed slowly over time and will decrease the rod pressure; (2) the decreasing cladding temperature also **decreases the hoop stress**, and this too will slow the creep rate **so that** during later stages of dry storage, **further creep deformation will become exceedingly small**; and (3) **in the unlikely event that a breach of the cladding due to creep occurs, it is believed that this will not result in gross rupture**. Based on these conclusions, the NRC staff has reasonable assurance that creep under normal conditions of storage will not cause gross rupture of the cladding and that the geometric configuration of the spent fuel will be preserved, provided that the maximum cladding temperature does not exceed 400°C (752°F). As discussed ..., **this temperature will also limit the amount of radially oriented hydrides that may form under normal conditions of storage.**”*

Transportation of High Burnup Fuel – *EPRI Conclusions*

- Modeling results using FEM
 - Accident conditions (9-m horizontal drop)
 - Sub-criticality
 - No *credible* conditions leading to a violation of the nuclear criticality safety requirements
 - Normal conditions (0.3-m horizontal drop)
 - Margin against axial flaw instability is very large
 - Guide tubes are susceptible to some deformation (ovalization)
- Transportation Issues Resolution
 - Based on EPRI's body of work, an approach for resolving remaining transportation issues was proposed
 - EPRI Report 1016637 "Transportation of Commercial Spent Nuclear Fuel – Regulatory Issues Resolution" (December 2010)

Cladding Performance R&D Drivers

- Confirmation of the technical bases used to formulate regulatory acceptance criteria for dry storing spent high-burnup fuel
 - DOE-EPRI North Anna project: similar to what was done for lower burnup fuel (NRC-EPRI-DOE INL project)
- New cladding materials (ZIRLO™, Optimized ZIRLO, M5, Zry-2 LK3)
 - Verify the properties of irradiated claddings used in high-burnup assembly designs
- Dry cask storage will likely be deployed for longer durations vs. originally anticipated
 - Could (extended) dry storage condition the high-burnup fuel in a manner that would be detrimental to making the safety case?
 - Transportability of fuel after extended storage?

“White Paper” on High Burnup Issue

- Main focus
 - PWR cladding performance
 - Storage and Transportation
- Topics not covered
 - DOE-EPRI North Anna High Burnup Project
 - Performance of BWR Barrier Cladding

Not Covered: North Anna Project – Expected Results

- Near term (first ~10 years)
 - Thermal benchmarking
 - Measured vs. calculated (licensing and best-estimate) *temperature distribution* inside the cask
 - Cladding integrity
 - ~8,400 rods in the cask
- Long term
 - Changes in fuel assembly materials properties driven by cladding stress
 - Thermal creep
 - Hydrogen/hydride behavior
 - Hydride re-orientation
 - Axial migration
 - DHC
 - Other observations?



Not Covered: BWR Barrier Cladding – Effect of Liner

[From EPRI Report 1025199 (2012)]

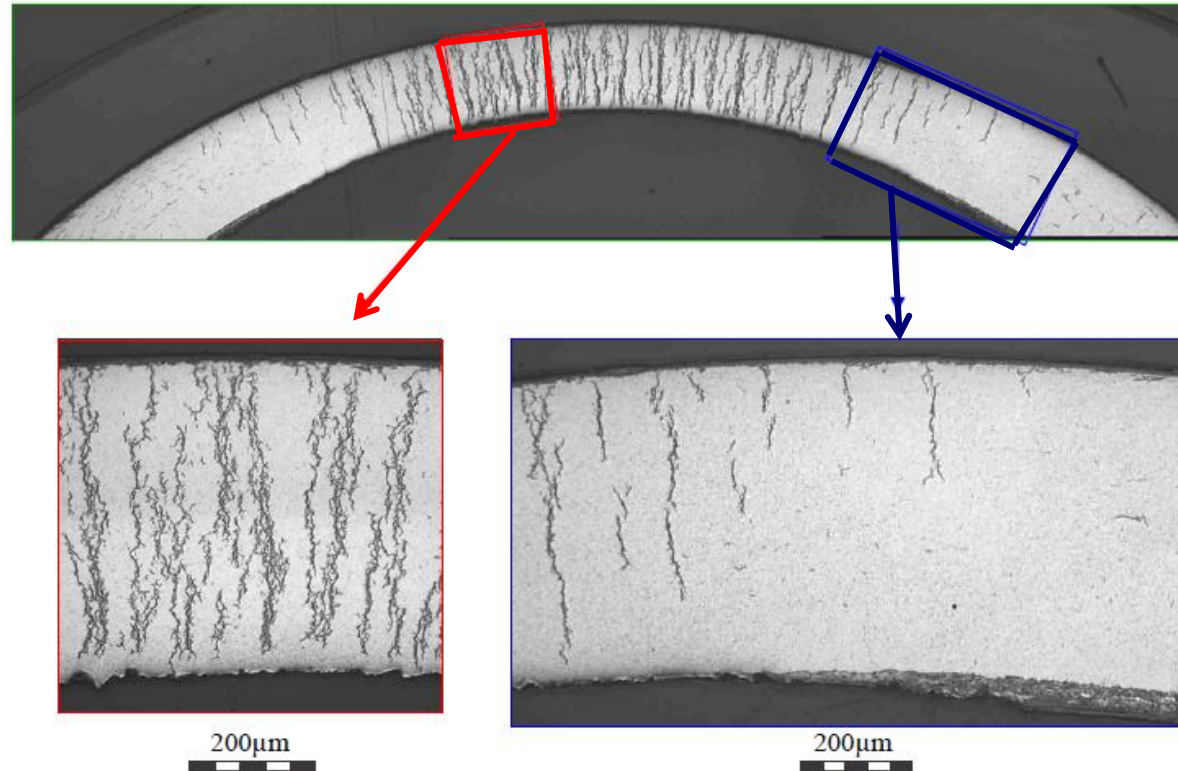


Figure 34 : Metallographic observation after task C treatment on Zircaloy-2 specimen 4H

Covered: PWR Cladding (Focus: High-burnup Applications)

■ Topics

- Introduction
 - Burnup
 - Discharge burnup
- Dry Storage
- Transportation
- Appendix A: Degradation Mechanisms

■ Subtopics

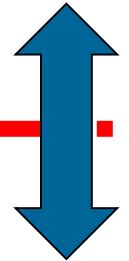
- Driving force for degradation mechanisms
- Published risk assessments
- Licensing considerations
- Performance verification/Industrial Experience
- Discussion
- Conclusion

Discharged PWR Assemblies (2000 – 2014)

[46,442 Assemblies]

Burnup Range	2014 Discharges	2013 Discharges	2012 Discharges	2000-2014 Discharges
≤ 45 GWd/MTU	34.0%	36.5%	30.4%	38.8%
45 to ≤ 50 GWd/MTU	38.3%	47.5%	45.6%	43.3%
50 to ≤ 55 GWd/MTU	23.8%	15.5%	22.6%	16.7%
≥ 55 GWd/MTU	3.9% ^a	0.5% ^b	1.4% ^c	1.3% ^d
	^a Highest burnup = 56.3 GWd/MTU (20 assemblies)			
	^b Highest burnup = 57.1 GWd/MTU (1 assembly)			
	^c Highest burnup = 56.5 GWd/MTU (4 assemblies)			
	^d Highest burnup = 70 GWd/MTU (1 lead-test assembly)			

“Low” Bu



“High” Bu

- Over the past 15 years:

EPRI Fuel REliability Database (FRED)

- Fraction of PWR assemblies with burnups ≤ 50 GWd/MTU is >80% and with burnups ≤ 55 GWd/MTU is > 98%
- Maximum discharge burnups do not appear to change
 - Assembly-average burnup limited by commercial reactor fuel license: rod-average burnup ≤ 62 GWd/MTU

Industrial Deployment

- Storage
 - >2 000 storage systems deployed in the US, and
 - >1 000 storage systems deployed outside the US, with
 - >20% of storage systems already contain high-burnup fuel
- Transportation
 - ~40 000 tons of spent LWR fuel transported (no dry storage before transport, but drying is implemented), with
 - ~10% being high-burnup fuel
 - If fuel performance expectations for dry storage are confirmed (i.e., limited hydride re-orientation), little or no differentiation whether or not dry storage is involved
 - Feedback from fuel handling operations at La Hague?

Dry Storage – Probabilistic Safety Assessments

Risk of Latent Cancer Fatalities

Storage Phase	EPRI-1009691 (2004) TN-32, bolted lid (PWR)	NUREG-1864 (2007) HI-STORM 100, welded lid (BWR)
Cask Loading/Handling	6.3×10^{-14}	1.8×10^{-12}
Cask Transfer	3.3×10^{-13}	≈ 0
Cask Storage	1.7×10^{-13}	3.2×10^{-14}
Sum of First Year	5.6×10^{-13}	1.8×10^{-12}

- PRAs are for a single dry cask/canister storage system
- Calculated risks are orders of magnitude between the recommended NMSS qualitative health goals and the risks indicated in the pilot PRAs

Transportation – Probabilistic Safety Assessments

- Radiological risks: very low [NUREG-2125 (published January 2014)]
 - Accidents \ll Normal conditions $<$ Background
- High-burnup-fuel-specific comments
 - For accidents that are severe enough to have a release path from the cask, all rods (high burnup or not) are assumed to fail
 - Differentiation between high burnup or low burnup requires
 - Knowledge of the rod-to-cask release fractions (but little to no difference based on published results)
 - Including greater amount of TRU's in high burnup fuel (impact smaller than one order of magnitude)

Dry Storage

- Dry storage of spent fuel, including high burnup fuel, is informed by probabilistic safety assessments and significant experience with deployment of the technology
- No or little re-orientation should be expected during dry storage
 - PWR Fuel Cladding
 - Missing data: DOE-EPRI North Anna High Burnup project
 - Prototypical (field) storage conditions
- Potential for very long-term degradation mechanisms
 - None expected, but storage for an indefinite period provides opportunities for speculative mechanisms
 - Present technical basis assumes that initial conditions (temperature and stress) will govern ensuing cladding performance

Dry Storage

- Contributing factors to expectations for no or little hydride re-orientation
 - Characteristics of U.S. PWR spent fuel inventory
 - Low driving forces for re-orientation (field vs. laboratory conditions)
 - Large margins in calculating drying, transfer and storage temperatures (Best-estimate feedback from the DOE-EPRI project)
 - Rod internal pressures change little with burnup up to existing licensing limits (rod-averaged burnup ≤ 62 GWd/MTU) [EPRI report 3002001949 (2013)]
 - Data gap: W Integral Fuel Burnable Absorber (IFBA) rods
 - Gap in mechanistic understanding: impact of fuel-cladding bonding

Transportation

- Transportation of high-burnup issues is similarly informed by probabilistic safety assessments, such as NUREG-2125, and by international experience
 - Confirmation of little to no hydride re-orientation during dry storage would obviously simplify the resolution of issues related to transportation (as was proposed in early 2000's)
 - However, the complete absence of hydride re-orientation is not a requirement for resolving transportation issues
 - Moderator exclusion, or
 - EPRI Report 1016637's approach



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